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Microbending Loss in Optical Fibers

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The loss induced in optical fibers by random bends in the fiber axis is studied by winding fibers under constant tension onto a drum surface that is not perfectly smooth. The tension forces the fibers to conform to slight surface irregularities, which can result in an increase in the optical loss on the order of 100 dB/km. This microbending loss may be a significant design consideration in system applications of low-loss optical fibers. Data are presented on the reduction of the effect by means of coatings and increased numerical aperture.

I. INTRODUCTION

For the full potential of presently available optical fibers to be realized, care will bave to be taken to minimize any perturbations tbat affect the fiber's transmission. One sucb perturbation is random bends in tbe axis of tbe fiber. Gloge[1] and Marcuse[2] bave sbown that sucb bends need not be of large amplitude to cause losses of a few decibels per kilometer. We bave found this "microbending loss" to be common in multifiber structures. Tbe worst of tbese structures add as mucb as 500 dB/km to the loss of the fibers. Although several decibel-per-kilometer added loss is more typical, tbe effect clearly poses a danger to system performance unless proper steps are taken to minimize it. Tbe following experimental study of microbending loss sbows bow it can be reduced by means of coatings and increased fiber numerical aperture.

II. EXPERIMENTAL TECHNIQUE

To obtain quantitative data on microbending loss, fibers were wound under controlled tension onto a drum wbose surface was not perfectly smooth. Tbe tension forced the fiber to partially conform to tbe surface roughness. The resulting random bending of tbe fiber axis caused a measurable increase in the optical loss. The drums were 10-in. diameter cast acrylic, and no rougbening of the polished surface was necessary to obtain measurable microbending loss.

The technique is illustrated in Fig. 1, where a continuous 455-m length of fiber is excited with a He-Ne laser. The left half was wound under 0.7 kg/mm^2 tensile stress and the right half under 7 kg/mm^2. It is seen from the scattering that the light is decaying much more rapidly in the right half. In fact, the microbending loss is 15 dB/km in the left half and 145 dB/km in the right half.

The method for winding the fibers is shown in Fig. 2. The pay-out shaft rides on low friction bearings and is splined to a hysteresis brake which generates a torque that is approximately independent of revolutions per minute. The torque is set by the current to the brake, and the resulting tension in the fiber is monitored with the polariscope to assure its constancy during winding. The polariscope is calibrated before each run by hanging weights on the pay-out drum while the brake is disconnected.

III. RESULTS

To determine the length dependence of the microbending loss, a Corning Glass Works (CGW) fiber with an inherent loss of 15 dB/km at 632.8 nm was wound with uniform pitch (20 turns/cm) at 2-kg/mm^2 tensile stress. A He-Ne laser beam was launched into the fiber, and the forward scattering was detected with a 1-cm-wide solar cell (appropriately baffled), whose edge was about 3 mm from the windings. Thus, the detector integrated the scattering from about 20 turns of

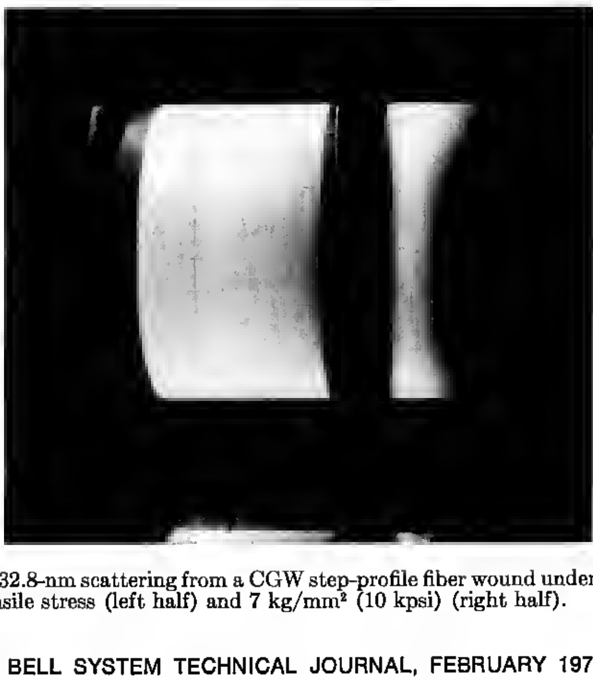

Fig. 1—632.8-nm scattering from a CGW step-profile fiber wound under 0.7 kg/mm^2 (1 kpsi) tensile stress (left half) and 7 kg/mm^2 (10 kpsi) (right half).

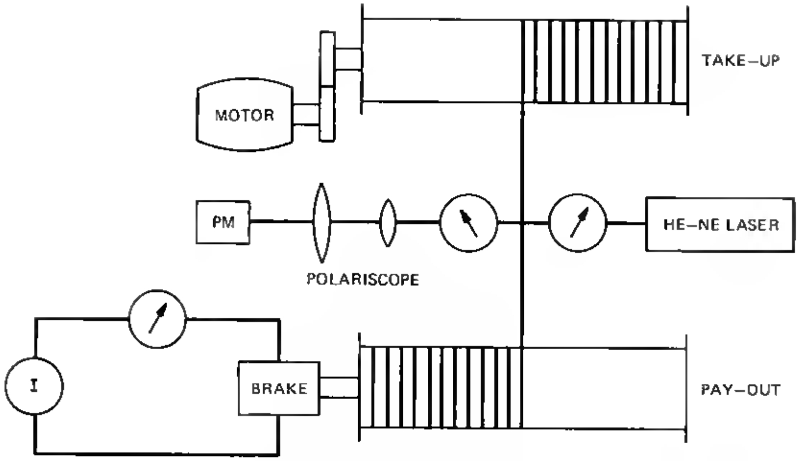

Fig. 2—Apparatus for winding fibers onto a drum under controlled tension.

the fiber. The detector was then translated parallel to the drum axis to generate the solid dots in Fig. 3. The fiber was then rewound under 0 kg/mm^2 and 4 kg/mm^2, and the scan repeated for each of these cases. Following the transient condition at the launching end, the curves become linear to within experimental error, and the slopes yield the attenuation coefficients shown. These numbers agree within experimental error with the total loss measured in the conventional way (by breaking a 1-ft length at the input end). Launching into the opposite end of the fiber did not alter the results. The linearity of the data in Fig. 3 shows the microbending attenuation coefficient γ to be independent of position along the fiber. This is to be expected when the statistics of the bending are not a function of position, and the energy distribution among the modes has reached equilibrium.

It has been shown that the microbending loss should decrease with increasing fiber numerical aperture for both parabolic[2] and step[3] index profiles. Experimental data for step-profile CGW fibers are shown in Fig. 4. The two fibers were similar except for their numerical apertures, and the microbending loss is plotted against the tensile winding stress. In a recent paper,[4] Gloge derived expressions for the microbending loss γ in both step and parabolic index fibers, assuming the spectral density of the drum roughness to be of the form

$$P(K) = P(0)/(1 + l^2K^2)^{\mu}. \tag{1}$$

Here, K is the mechanical wave number $2\pi/\Lambda$, and l has the physical significance of a correlation distance. Gloge has derived[4] a general expression for γ in terms of the parameters l and μ. This expression is

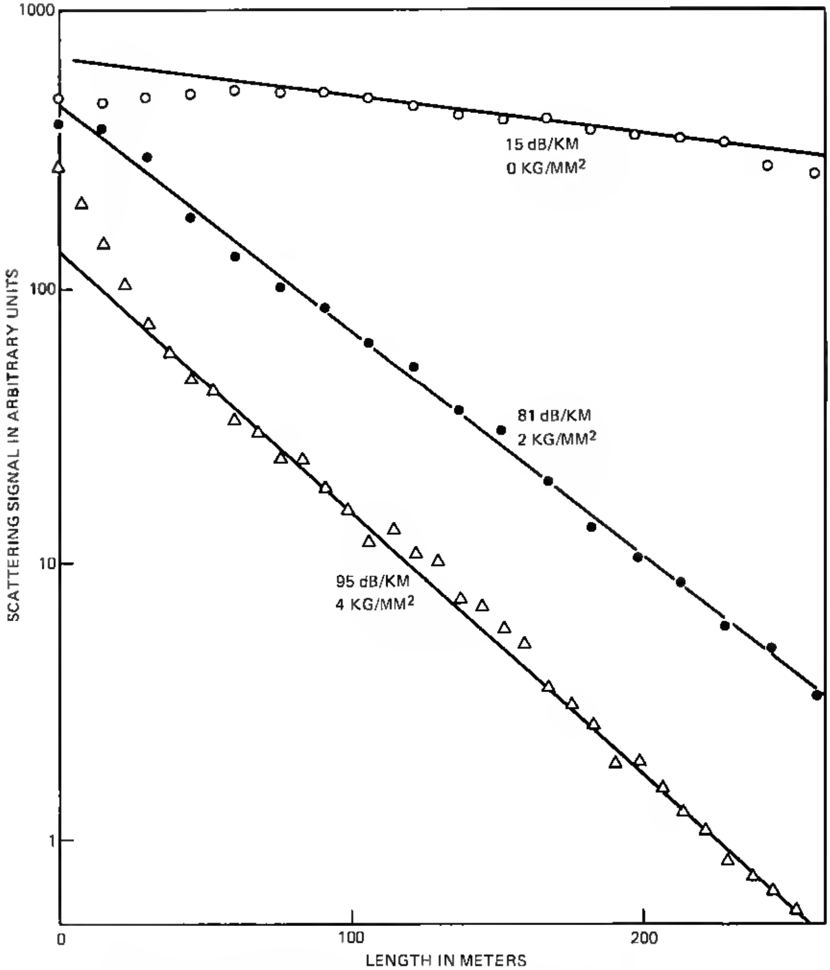

Fig. 3—632.8-nm scattering from a CGW step-profile fiber with $a_c = 44$ μm, $a_0 = 66$ μm, N.A. = 0.120.

consistent with the $\gamma \propto (\text{N.A.})^{-4.3}$ dependence manifested in Fig. 4, when $\mu = 3.1$. Setting $\mu = 3$ in the expression gives the following upper limit for the microbending loss in a step profile fiber:

$$\gamma \leqq \frac{3\sigma^2 a_c^2/2\pi l^5 \Delta^2}{(1 + 144\Delta^4 H^2/25 a_c^8 D^2)(1 + 64\sigma^4 H^{\frac{1}{2}} D^{\frac{3}{2}}/225 f_0^4 l^{10})^{\frac{1}{2}}}, \tag{2}$$

where

σ = rms drum roughness
a_c = core radius

$$\begin{aligned} \Delta &= \text{(core index} - \text{cladding index)/(core index)} \\ &= (\text{N.A.})^2/2n^2 \\ H &= \text{flexural rigidity} \\ D &= \text{lateral rigidity} \\ f_0 &= \text{normal force per unit length of fiber} \\ &= \text{(tensile winding force)/(drum radius).} \end{aligned}$$

For an uncoated fiber of Young's modulus E_f and outer radius a_0 wound onto a drum of Young's modulus E_d, we have

$$H = \pi E_f a_0^4/4 \quad \text{and} \quad D \cong E_d. \tag{3}$$

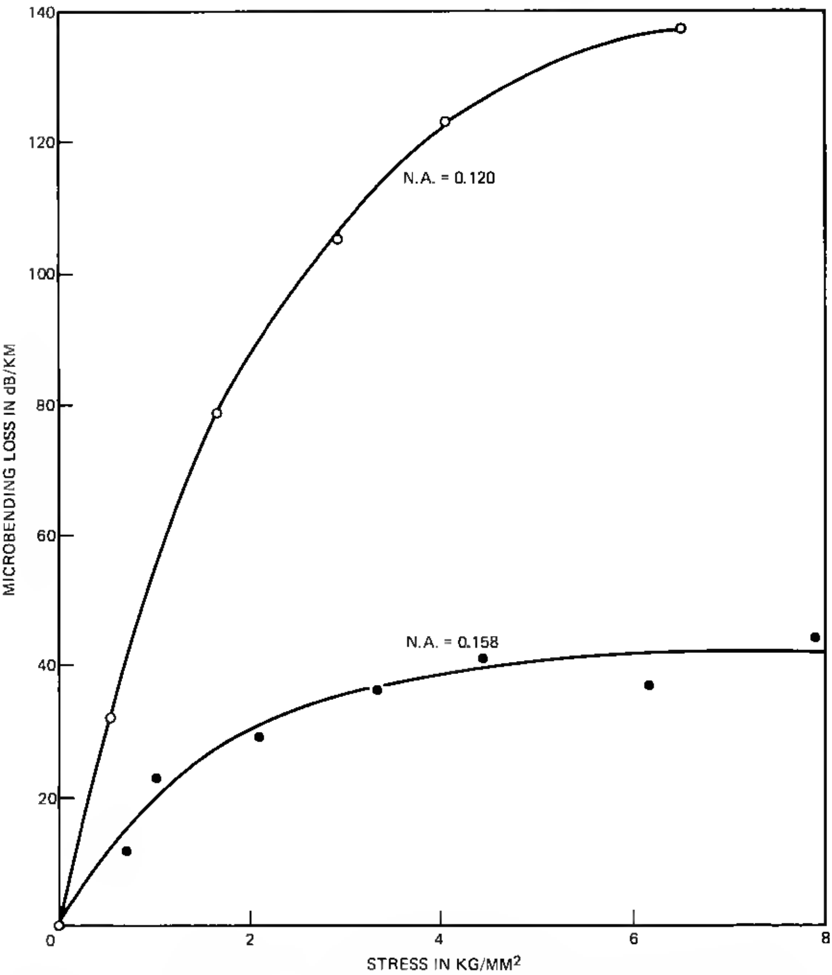

Fig. 4—γ vs winding stress at 632.8 nm for two CGW step-profile fibers which are similar except for their N.A.'s. $a_c = 44\ \mu\text{m}$, $a_0 = 66\ \mu\text{m}$, and the lengths were about 200 m.

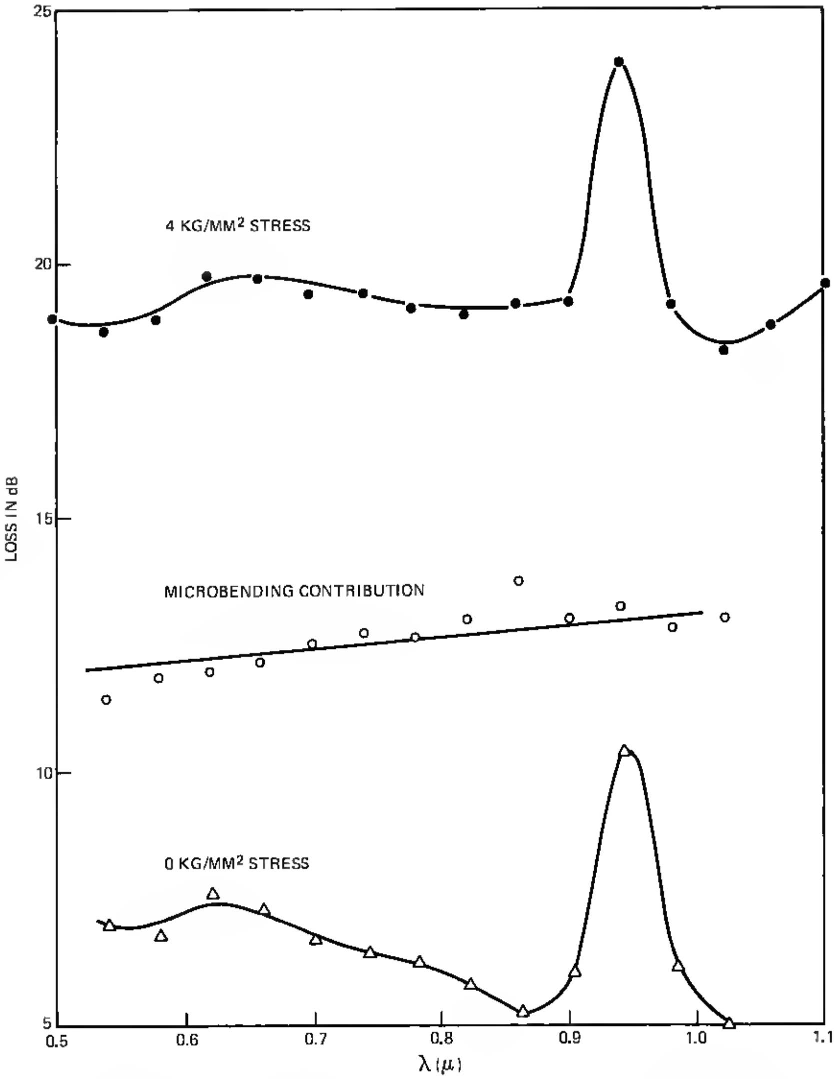

Fig. 5—Spectral loss curves showing that the added loss under stress is almost wavelength-independent.

Equation (2) assumes that l is large compared to both $K_c^{-1} = a_c/(2\Delta)^{\frac{1}{2}}$ and $(H/D)^{\frac{1}{4}}$, which are typically a few tenths of a millimeter.

Although the spectrum (1) with $\mu = 3.1$ leads to $\gamma \propto (\text{N.A.})^{-4.3}$, any other roughness (whether from coatings, drums, packaging, or whatever) will likely have a different spectral density and hence cause a different dependence of γ on numerical aperture.

There is no explicit dependence on optical wavelength in eq. (2). As a test of this, a spectral loss curve was obtained for a 160-m length CGW fiber wound first under 4-kg/mm² stress and then 0 kg/mm². Subtracting the lower curve from the upper curve in Fig. 5 gives the microbending contribution, which is indeed almost wavelength-independent. The very slight dependence on λ may be a result of dispersion in the fiber's relative index difference Δ. Similarly, measurements of the γ induced in 14 different fibers by multifiber structures were the same (within experimental error) at 0.64 μm as at 0.84 μm.

According to eq. (2), γ should be proportional to f_0 for small f_0. As $f_0 \rightarrow \infty$, however, the fiber fully conforms to the roughness, and γ becomes independent of f_0. Since f_0 is proportional to the winding stress, the shape of the Fig. 4 curves is consistent with this prediction. The value of f_0 corresponding to the transition between these two regimes can be predicted from eq. (2). The predicted value is several times larger than the measured value (which corresponds to about 3 kg/mm² stress) from Fig. 4. This may be because adjacent turns of the fiber are not isolated, a fact which is evident from a measured decrease in γ with increasing winding pitch. For this reason, the same pitch (20 turns/cm) was used for all measurements.

Letting $f_0 \rightarrow \infty$ in (2) and setting γ equal to the asymptotic value of the N.A. = 0.158 curve in Fig. 4 yields $\sigma^2/l^5 = 0.4 \times 10^{-6}$ mm^{-3}. A correlation distance of $l = 1$ mm, for example, would then imply $\sigma = 0.6$ μm. The existence of roughness of this magnitude is not surprising, despite the polished appearance of the surface. A 0.6-μm variation over a distance of 1 mm would be difficult to measure.

For the acrylic drum used, $D = 280$ kg/mm² (400 kpsi), and with the fibers used, $144\Delta^4 H^2/25a_c^8 D^2 \ll 1$, so that, in the limit of small f_0, (2) becomes

$$\gamma_0 \leqq \frac{0.76\sigma a_c^2 f_0}{l^{\frac{3}{2}}\Delta^2 a_0^{\frac{5}{2}} E_f^{\frac{5}{8}} D^{3/8}}. \tag{4}$$

From this expression, it is evident that a small core radius and large outer radius is desirable for minimizing microbending loss. The minimum usable core radius may be determined by splicing considerations, and the maximum outer radius by the bending which the fiber is required to withstand without breaking. The microbending also increases the penetration of the evanescent wave into the cladding,[5] thus possibly making thicker cladding necessary for adequate optical isolation.

In addition to maximizing Δ and a_0 and minimizing a_c and σ, a further option is available for minimizing γ. This is to encapsulate the fiber in a compliant medium. The requirements for the encapsulant are that it be thick and uniform. The case of a homogeneous coating is illustrated in Fig. 6. The linearity of these curves is probably due to a larger σ for the acrylic drum surface used here than for the one used in Fig. 4. The coating applied to the fiber was DuPont *Elvax*® 265, a co-polymer of ethylene and vinyl acetate. The coating was 50 μm thick, with a modulus of $E_c = 1.4$ kg/mm² (2000 psi), and was applied

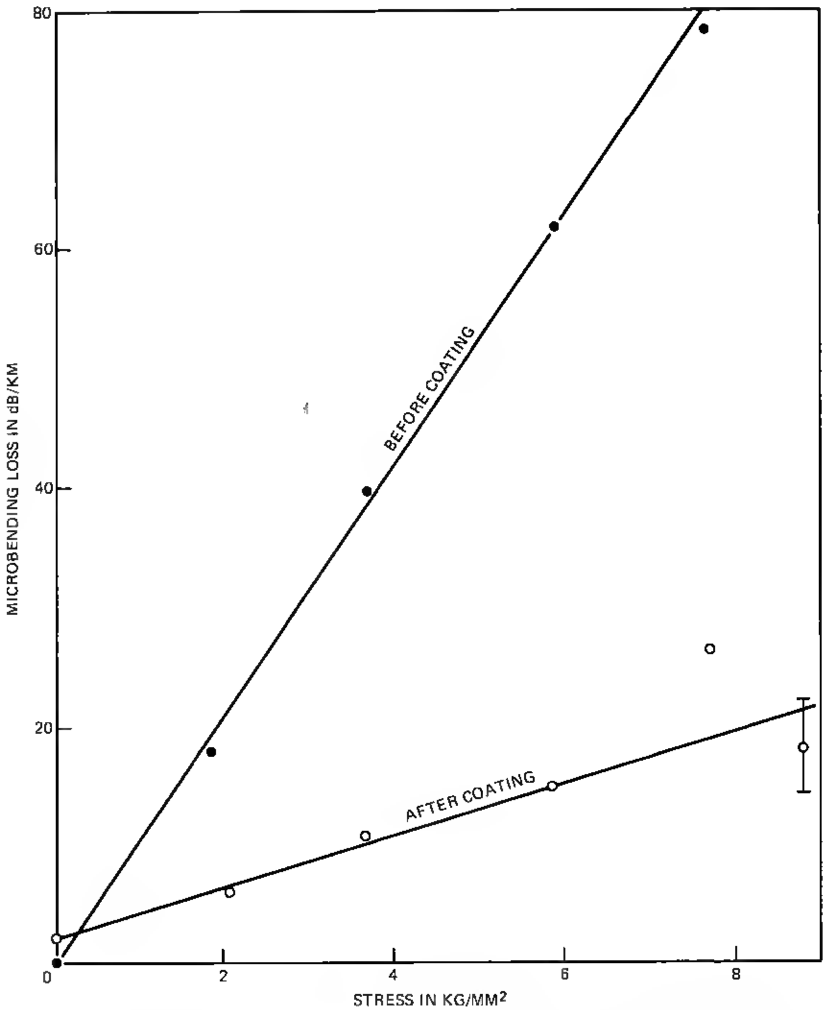

Fig. 6—γ vs winding stress at 632.8 nm before and after coating a CGW step profile fiber with a 50-μm thickness of DuPont *Elvax*® 265. The fiber was 180 meters long with $a_c = 43$ μm, $a_0 = 66$ μm, and N.A. = 0.160.

with a die technique. After the fiber is coated, D in (2) becomes $(E_d^{-1} + E_c^{-1})^{-1} \cong E_c$, while H is only slightly changed. In order for Gloge's general expression[4] for γ to predict the observed reduction in γ of a factor of 4.3 in the small f_0 regime owing to a uniform coating, μ must equal 4.4. The discrepancy between this and the value $\mu = 3.1$ (deduced from the N.A. dependence) may be an indication that the assumption of perfect coating uniformity is invalid. In that case, the coating thickness variation spectrum would add to the drum roughness spectrum, creating a new composite spectrum. Also, despite careful cleaning of the drum, it is possible that foreign material with a modulus different from E_d may make some contribution to the microbending.

IV. SUMMARY AND CONCLUSIONS

The microbending caused when an optical fiber is forced to conform to small irregularities is shown to be capable of causing sufficient optical loss to affect the performance of a communication system. Studies involving the winding of fibers under tension onto drums show significant reduction in the effect by means of coatings and increased fiber numerical aperture. Studies of multifiber structures are currently in progress and suggest that, with proper care and knowledge in design, the effect can be reduced to an acceptable level.

V. ACKNOWLEDGMENTS

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